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Volcanic Eruptions and Solar Activity

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The historical record of large volcanic eruptions from 1500 to 1980, as contained in two recent eruption catalogs, is subjected to detailed time series analysis. Two weak, but probably statistically significant, periodicities of ~11 and ~80 years are detected. Both cycles appear to correlate with well-known cycles of solar activity; the phasing is such that the frequency of volcanic eruptions increases (decreases) slightly around the times of solar minimum (maximum). The weak quasi-biennial solar cycle is not obviously seen in the eruption data, nor are the two slow lunar tidal cycles of 8.85 and 18.6 years. Time series analysis of the volcanogenic acidities in a deep ice core from Greenland, covering the years 553–1972, reveals several very long periods that range from ~80 to ~350 years and are similar to the very slow solar cycles previously detected in auroral and carbon 14 records. Mechanisms to explain the Sun-volcano link probably involve induced changes in the basic state of the atmosphere. Solar flares are believed to cause changes in atmospheric circulation patterns that abruptly alter the Earth's spin. The resulting jolt probably triggers small earthquakes which may temporarily relieve some of the stress in volcanic magma chambers, thereby weakening, postponing, or even aborting imminent large eruptions. In addition, decreased atmospheric precipitation around the years of solar maximum may cause a relative deficit of phreatomagmatic eruptions at those times.

INTRODUCTION

Searches for a possible volcanic eruption cycle in phase with the 11-year cycle of solar activity have led to very conflicting results. *Kluge* [1863*a*, *b*] and some early successors [*De Marchi*, 1895; *Köppen*, 1896, 1914; *Jensen*, 1902, 1904] suggested that global volcanic activity increases noticeably during times of reduced solar activity as shown by low annual mean relative sunspot numbers. Other authors, however, have argued that volcanic eruptions tend to be concentrated near the times of both solar minimum and solar maximum [*Poëy*, 1874; *Swinton*, 1883; *O'Reilly*, 1899; *Lockyer*, 1902]. Hawaiian eruptions, paradoxically, have been variously associated with solar minimum [*Lyons*, 1899], solar maximum [*Jaggar*, 1931, 1938, 1947], and no special solar phase at all [*Stearns and Macdonald*, 1946; *Macdonald*, 1960]. Despite two earlier suggestions that Fayal in the Azores preferentially erupts close to solar maximum [*Machado*, 1960; *de Mendoça Dias*, 1962], the evidence for a general association between middle Atlantic volcanic eruptions and the solar cycle seems to be inconclusive [*Mitchell-Thomé*, 1981]. The utilization of more volcanoes from all over the globe has led two other authors to deny any correlation between volcanic eruptions and solar activity [*Espin*, 1902; *Sapper*, 1927, 1930]. Yet no formal statistical tests of significance were ever performed to support the claimed presence or absence of such a correlation. Conclusions were based merely on visual inspection of tables or graphs. A single exception was the statistical analysis by *Abdurakhmanov et al.* [1976], whose sample of 39 eruptions, however, is too small to reveal the claimed correlation in a convincing manner.

Long-term lunar tidal cycles have also been looked for in various volcanic records. Both the 8.85-year lunar tidal cycle [*Espin*, 1902; *Hamilton*, 1973] and the 18.6-year one [*Zenger*, 1904; *Hamilton*, 1973; *Alexeev*, 1989] are thought to be possibly present in global volcanism. Claims of an 18.6-year tidal cycle in local eruptions, for example, in the middle Atlantic Ocean (*Machado* [1960, 1967]; but see *Mitchell-Thomé* [1981]), Hawaii [*Wood*, 1917], Kamchatka [*Shirokov*, 1983], and Yellowstone Park [*Rinehart*, 1972*a*], have also been made. But, again, no rigorous statistical tests were applied, except in the case of the Yellowstone Park geysers for which the record was only about two cycles long.

An unexpected cycle of 7 or 8 years was found by *Kelly* [1977*a*] in *Lamb*'s [1970] time series of the volcanic dust veil index (dvi). The cycle's origin was speculatively attributed to interaction between the annual component of the Earth's polar wander and the Chandler wobble period of about 14 months. Later, the cycle was demonstrated to be merely an artifact of *Lamb*'s [1970] formulation of the dvi [*Chance and Kelly*, 1979].

There are now available for study a large number of documented volcanic eruptions listed in two new volcano catalogs [*Simkin et al.*, 1981; *Newhall and Self*, 1982]. These detailed catalogs, which are related in content to each other, have recently been used to demonstrate statistically the improbability of a significant seasonal or annual cycle in global volcanism [*Stothers*, 1989]. The present investigation looks for possible volcanic cycles with longer periods that might be attributed to the influence of solar activity and lunar tidal forces. Shorter-period volcanic cycles will not be discussed in any detail here.

VOLCANO CATALOGS

Dated eruptions accepted for use in this study come from the recent compilations by *Simkin et al.* [1981] and *Newhall and Self* [1982]. The larger catalog of *Simkin et al.* [1981] covers 5564 known eruptions of all kinds between 8000 B.C. and A.D. 1980, while the smaller catalog of *Newhall and Self* [1982], who estimated all the explosivity strengths in both catalogs, contains only the 122 most explosive eruptions from A.D. 1500 to A.D. 1980. (Some of the eruption dates listed by *Newhall and Self* [1982] are erroneous, and the dates of *Simkin et al.* [1981] should be used instead.) In these catalogs, eruptions have been classified according to a

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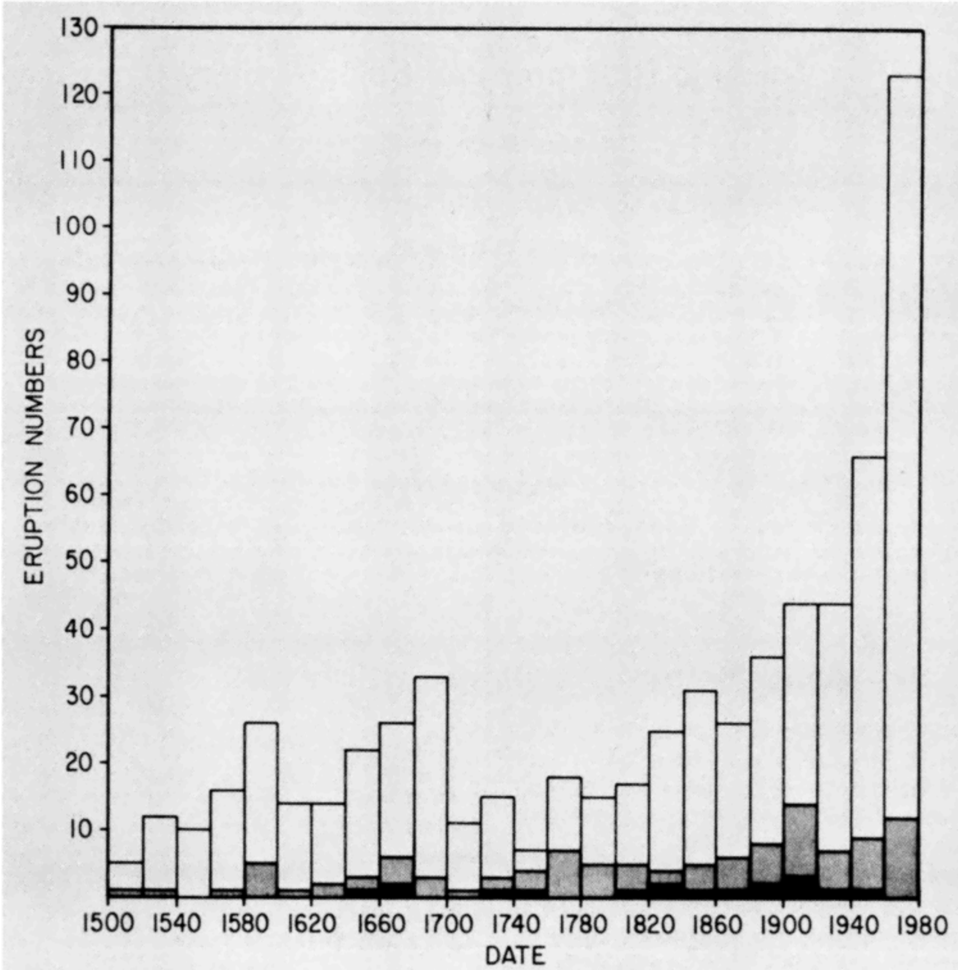

Fig. 1. Frequencies of reported large volcanic eruptions between the years 1500 and 1979 plotted in bins of width 20 years. Black, VEI ≥ 5; grey, VEI = 4; white, VEI = 3.

semiquantitatively based Volcanic Explosivity Index (VEI = 0 for very small effusive eruptions to VEI = 8 for the largest explosive eruptions). Rankings of eruptions by VEI are usually uncertain for all but the largest and best documented cases; in fact, a VEI of 2 has served largely as a default category. For this reason and to avoid inclusion of a lot of minor phenomena that may be merely precursors or aftereffects of major eruptions, only eruptions with VEI ≥ 3 are used here. Uncertainty attached to a published VEI designation (with a question mark or a plus sign) is ignored, but eruptions whose occurrences are denoted as being in significant doubt are rejected. In a small number of cases, the day or even the month of the eruption is ambiguous since the activity consisted of a closely spaced succession of large eruptions. The date of the first eruption in such a series has been accepted for use here.

As exhaustive as these two catalogs are, the regional and temporal coverages of eruptions are very spotty, especially for the period before the sixteenth century. Eruption dates falling in the modern period 1500–1979 and known to the exact year are plotted in a histogram in Figure 1. The bin size used is 20 years, and eruption frequencies are given separately for VEI ≥ 5, VEI = 4, and VEI = 3. An analysis by *Newhall and Self* [1982] has shown that relative completeness of the dates only begins around 1800 for VEI ≥ 5, around 1900 for VEI = 4, and around 1960 for VEI = 3. The striking increase in VEI = 3 eruption frequencies since 1800 reflects merely the progressive improvement in observing and reporting the smaller eruptions [*Newhall and Self*, 1982], not an actual increase of worldwide volcanism. Since an arbitrary, though useful, upgrading of the VEI by one unit was applied to many eruptions before 1700 to minimize early reporting bias, an artificial discontinuity separates the eruption numbers before and after that year and affects mainly the VEI = 3 eruption numbers [*Newhall and Self*, 1982]. Historical factors may account for some of the other short-term irregularities in Figure 1 [*Simkin et al.*, 1981]. On the whole, however, given the length (481 years) of the time series, it is reasonable to regard the record as roughly stationary for VEI ≥ 4 and, at least before 1900, for VEI = 3, if the purpose is to look for possible volcanic periods shorter than 100 years. In general, incompleteness of a volcanic record and even the presence of a monotonically growing (or decaying) nonstationarity is not a real problem as long as omissions are approximately random or, if not, are at least approximately systematic in an easily discernible way.

METHOD OF TIME SERIES ANALYSIS

Period searching is accomplished here by using the method of linear spectral analysis [*Stothers*, 1979], in which the observed dates of events t_i ($i = 1, 2, \cdots, N$) are matched to the closest times of maximum predicted from a linear model $t = t_0 + nP + \varepsilon$, where P is a trial period, t_0 is a trial phase, and n is a running integer. The adopted goodness-of-fit criterion is defined by numerically locating the smallest rms residual σ (and hence the best phase) for each trial period, dividing σ by the trial period, and then subtracting the quotient from a numerical constant $\sigma_c/P = [(N^2 - 1)/12N^2]^{1/2}$; this yields $(\sigma_c - \sigma)/P$, simply called the "residuals index." Linear spectral analysis is effective at locating periodicities (or quasi-periodicities) in a series of dates where considerable noise and incompleteness are present and sparseness makes binning of the dates unfeasible. It works well even in the presence of large nonstationarities in the series of dates [*Stothers*, 1986].

Autocorrelation analysis is not a suitable tool here because of the gaps and other nonstationarities in the time series. Application of Fourier analysis, although also not really appropriate, yields essentially the same spectral peaks as does linear spectral analysis, especially if the two spectra are normalized to the same vertical scale. Exceptions obviously occur near the Nyquist frequency and also near the record-length frequency, where standard Fourier analysis techniques (like the periodogram method) show poor resolution. This problem can be overcome by using maximum entropy spectral analysis. Since standard Fourier analysis and the maximum entropy method, with or without binning of the dates, have recently been shown to give intermediate-frequency spectral results that are very similar to those provided by linear spectral analysis in two typical geophysical applications for both dense and sparse time series [*Rampino and Stothers*, 1984, note 31; *Stothers*, 1986], it is sufficient here to adopt linear spectral analysis. In any case, this is the more logical and appropriate method to use for the present type of time series.

THE 11-YEAR CYCLE

The dates of 114 eruptions that were assigned VEI ≥ 4 and occurred between the years 1500 and 1980 are analyzed first. A spectrum of the residuals indices is shown for trial periods of 2–100 years in Figure 2*a*, where the highest spectral peak appears at P = 10.8 years. (To avoid crowding, only the highest spectral peaks are shown for $P < 13$ years.) Division of the eruption time series into two contiguous intervals, 1500–1699 and 1700–1980, does not change the derived value of this period. To look for a possible dependence on geographical latitude, three basic climatic zones are considered: southern latitudes, 90°S to 30°S; equatorial latitudes, 30°S to 30°N; and northern latitudes, 30°N to 90°N. The main spectral peak still occurs at P = 10.8 years for the 52 equatorial eruptions but shifts slightly to P = 11.2 years, while keeping about the same height, for the 56 northern eruptions; six southern eruptions are too few to analyze. Assuming a range of a priori periods equal to 9.5–11.5 years (which will be justified below), Monte Carlo tests for statistical significance are performed by generating and then analyzing 1000 simulated time series, each consisting of 114 dates randomly selected from the interval 1500–1980 and set in chronological order. The resulting spectra display higher peaks than the main peak shown in Figure 2*a* in only 3% of the cases; therefore the null hypothesis that the observed series of eruption dates is random can be rejected with 97% confidence.

To enlarge the data set, the analysis is next repeated for 380 eruptions with VEI ≥ 3, covering the restricted time interval 1500–1900 because eruption numbers for VEI = 3 begin to diverge rapidly from approximate stationarity after about 1900 (Figure 1). The highest peak in the resulting spectrum (Figure 2*b*) emerges from the background of minor peaks more clearly than before owing to the larger number of eruptions, but the period shifts to 9.5 years. By again assuming 9.5–11.5 years as the appropriate range of a priori periods, the derived confidence level comes out to be 99.5%. Even with no effective constraint on the possible periods, say by testing over the range 5–100 years, confidence remains high at 95%.

In evaluating the significance of the spectral peaks in these tests, an average a priori period of 10.5 ± 1 years has been chosen in order to investigate a possible dependence of volcanic activity on solar surface activity. The Sun has in fact displayed, over the time span of detailed observations since 1640, a marked quasi-period of 11.1 ± 0.1 years (called the Schwabe-Wolf cycle), as seen, for example, in annual mean relative sunspot numbers. Since the intervals between successive maxima actually range from 7 to 17 years, long stretches of time can be characterized by a mean length for the cycle that lies anywhere between 9.5 and 11.5 years [*Robbins*, 1984].

Owing to this irregularity, several reasons exist for expecting that the cycle of 9.5 or 10.8 years derived for volcanic eruptions might be slightly less than the simply predicted value of 11.1 years. First, the analysis of volcanic eruption frequencies was disproportionately weighted by the two time intervals 1640–1700 and 1820–1980, during which eruptions occurred somewhat more frequently (or were more frequently recorded or were later ranked higher) than the average, but the mean sunspot cycle lengths were only 10.4 years and 10.6 years, respectively, as has been determined from sunspot data compiled by *Eddy* [1976, 1983] (for 1640–1699), *Waldmeier* [1961] (for 1700–1960), and *U.S. Department of Commerce* [1987] (for 1961–1980). The sunspot data before 1700, however, are not very reliable.

Second, the use of many somewhat smaller eruptions with VEI = 3 increases the likelihood of getting accidental clusterings of eruption dates that behave like additional maxima and so skew the best-fit period toward smaller values. Numerical experiments performed on a time series consisting of the 26 actual years of sunspot maximum between 1700 and 1980 show that there is a 5% chance of obtaining a best fit period of 10 years or shorter with the present method of analysis if as few as 7 additional, randomly generated years are inserted chronologically into the time series.

Third, even with no extra eruption frequency maxima added, minor accidental shifts of the true peaks in the eruption frequency distribution probably occur to some extent as a result of small number fluctuations, and this random jiggling will also alter the best fit period. Numerical simulations, again using the 26 years of sunspot maximum between 1700 and 1980, show that the best fit period has a 5% chance of equalling or falling shorter than 10 years if randomly applied departures from the true times of maximum lie within the small range ±2 years.

Fourth, in the case of both VEI ≥ 4 and VEI ≥ 3 eruptions, a total of seven distinct spectral peaks actually occurs between trial periods of 9 and 13 years (Figure 3). In

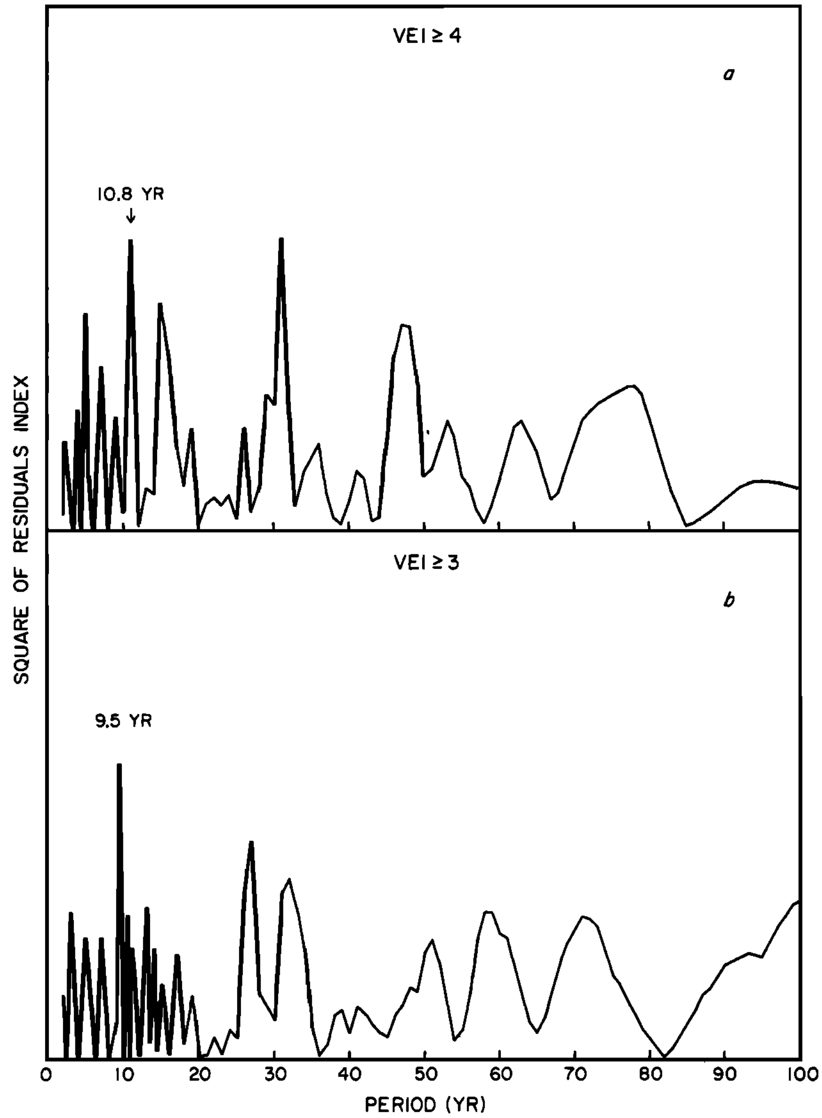

Fig. 2. Spectrum of the square of the residuals index for two long time series of large volcanic eruptions. The residuals index is a measure of goodness-of-fit of the observed time series to an assumed, perfectly periodic time series. Only the highest spectral peaks are shown for periods shorter than 13 years. The vertical scale is arbitrary. (*a*) VEI ≥ 4, t = 1500–1980, and N = 114. (*b*) VEI ≥ 3, t = 1500–1900, and N = 380.

the sunspot case, spectral peaks having similar periods of 8.8, 9.4, 10.0, 10.6, 11.1, 12.1, and 12.9 years (with variations of up to ±0.2 year) have already been detected by Fourier analysis and related techniques [*Cole*, 1973; *Sneyers*, 1976; *Lomb and Andersen*, 1980; *Otaola and Zenteno*, 1983; *Robbins*, 1983] and are confirmed here by linear spectral analysis of the 26 years of sunspot maximum between 1700 and 1980. Numerical tests show that a slight randomization of the years of sunspot maximum within ±2 years always causes one of these seven periods to be picked as the best fit period.

Fifth, other high spectral peaks for both VEI ≥ 4 and VEI ≥ 3 eruptions occur at periods of ~16, ~30, ~50, ~60, and ~75 years. Since similar peaks appear at periods of 15 ± 1, 26 ± 2, 47 ± 3, 59 ± 4, and 90 ± 10 years in the spectra for annual mean relative sunspot numbers (see above and *Gleissberg* [1958], *Cohen and Lintz* [1974], and *Wittmann* [1978]), the overall resemblance between volcanic and sunspot period structures seems to be confirmed. Although the spectral peaks for volcanic eruptions with periods of ~16, ~30, ~50, and ~60 years are relatively high compared to their sunspot spectral counterparts, "noise" in the volcanic time series probably accounts for this difference, since these four spectral peaks exhibit little statistical significance unless the associated periods are tested as a priori periods (that is, as periods known from the sunspot record). It is noteworthy that in neither the volcanic nor the sunspot case does a peak occur near the 22 years period of the Sun's magnetic (Hale) cycle. Although volcanic periods of 35 years [*Jensen*, 1902], 55 years [*Hamilton*, 1973], and 100 years [*Kluge*, 1863*a*] have previously been suspected, with two of them even being associated with possible sunspot periods, the data that suggested them cannot now be considered as adequately abundant to support the identifications.

Phase information also suggests that the ~11-year volcanic cycle is connected with solar activity. Although a meaningful cross-correlation study would require a resolution of ~1 year and so is not practical here owing to the

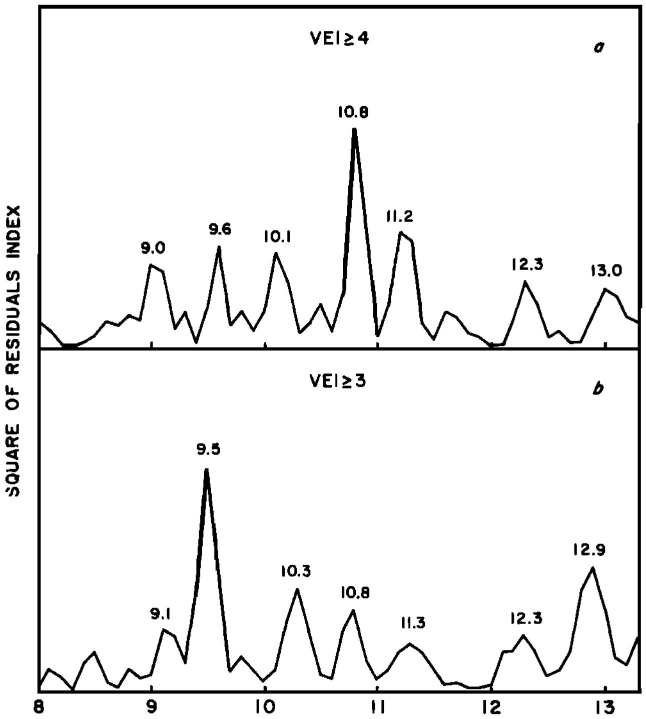

Fig. 3. Detail of Figure 2 for trial periods of 8–13 years.

sparseness and incompleteness of the volcanic time series, a superposed epoch analysis for the time interval 1700–1980 can be used to estimate the phase relations of VEI $\geq$ 4 eruptions to sunspot maximum and minimum. To display the results, a plot is made of the differences between the numbers of eruptions phased with respect to sunspot minimum minus the numbers of eruptions phased with respect to sunspot maximum (Figure 4*a*). In assessing this plot, it must be remembered that, although spectral analysis is able to pick out a significant period from amid much noise, superposed epoch analysis always displays the noise along with the signal. Nevertheless, in spite of the noise, eruption numbers are seen to increase slightly around the years of sunspot minimum as compared to sunspot maximum. The temporal spread of the eruption numbers between peak and mean values is about $\pm$2.5 years. A similar result has been obtained for VEI $\geq$ 5 and VEI $\geq$ 3 eruptions. Since the superposed epoch analysis shows, in effect, the formal residuals of the linear spectral analysis, it represents the same statistically significant result.

To compare Figure 4*a* with analogous plots for extreme solar phenomena [*Newton and Milsom*, 1954; *Das Gupta and Basu*, 1965; *Gnevyshev*, 1967; *Goswami et al.*, 1988], two well-studied phenomena are chosen: the largest sunspot groups, having an average area of more than 1500 millionths of the surface of the solar hemisphere, for the years 1874–1964 [*Spencer Jones*, 1955; *Kopecký and Kotrč*, 1974], and the strongest geomagnetic storms at Greenwich, for the years 1840–1954 [*Spencer Jones*, 1955]. Results are shown in Figures 4*b* and 4*c*, the vertical scales having been inverted to facilitate comparison with Figure 4*a*. The distributions display temporal spreads of $\pm$2.5 years, in agreement with what was found for volcanic eruptions.

For VEI $\geq$ 3 eruptions, the statistics are sufficiently

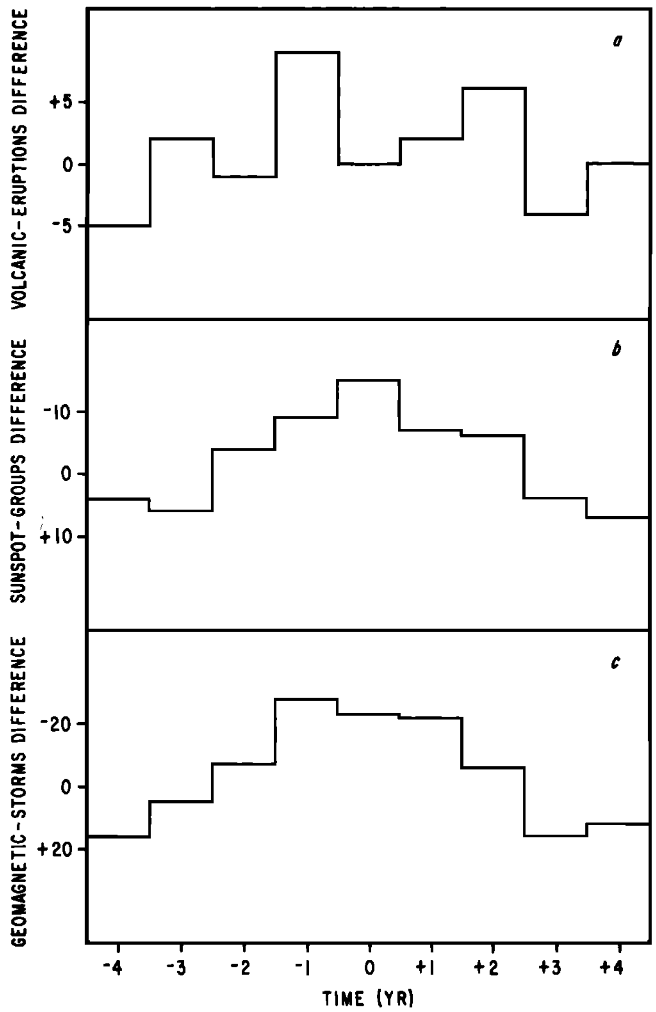

Fig. 4. Superposed epoch analyses of volcanic and solar phenomena between the years 1700 and 1980. "Differences" are the numbers of events phased with respect to sunspot minimum minus the numbers of events phased with respect to sunspot maximum. Epoch "zero" refers to both sunspot minimum and sunspot maximum. (*a*) Volcanic eruptions with VEI $\geq$ 4, 1700–1980. (*b*) Largest sunspot groups, 1874–1964. (*c*) Strongest geomagnetic storms, 1840–1954. Note that the vertical scale in Figures 4*b* and 4*c* is inverted.

numerous during the twentieth century to bin the data in 1-year intervals. After smoothing the annual eruption numbers with a filter that takes 5-year running means in order to display long-term trends freed of most of the interannual noise, the resulting time curve is shown in Figure 5. (The choice of 5 years for the window is unimportant; 3 years yield approximately the same appearance in the figure.) Superimposed on the growing background is a mild cyclical fluctuation, for which Fourier spectral analysis gives a best fit period of 10.0 $\pm$ 0.2 years. This reasonably clear periodicity independently confirms the results presented above for VEI $\geq$ 3 eruptions, because the preceding time series analysis did not use the twentieth century data. Fourier spectral analysis of 5-year running means for annual mean relative sunspot numbers during the twentieth century also gives a best fit period of 10.2 $\pm$ 0.2 years. Arrows on Figure 5 indicate the years of solar minimum. Why the solar minimum year 1976 fails to correspond to a volcanic maxi-

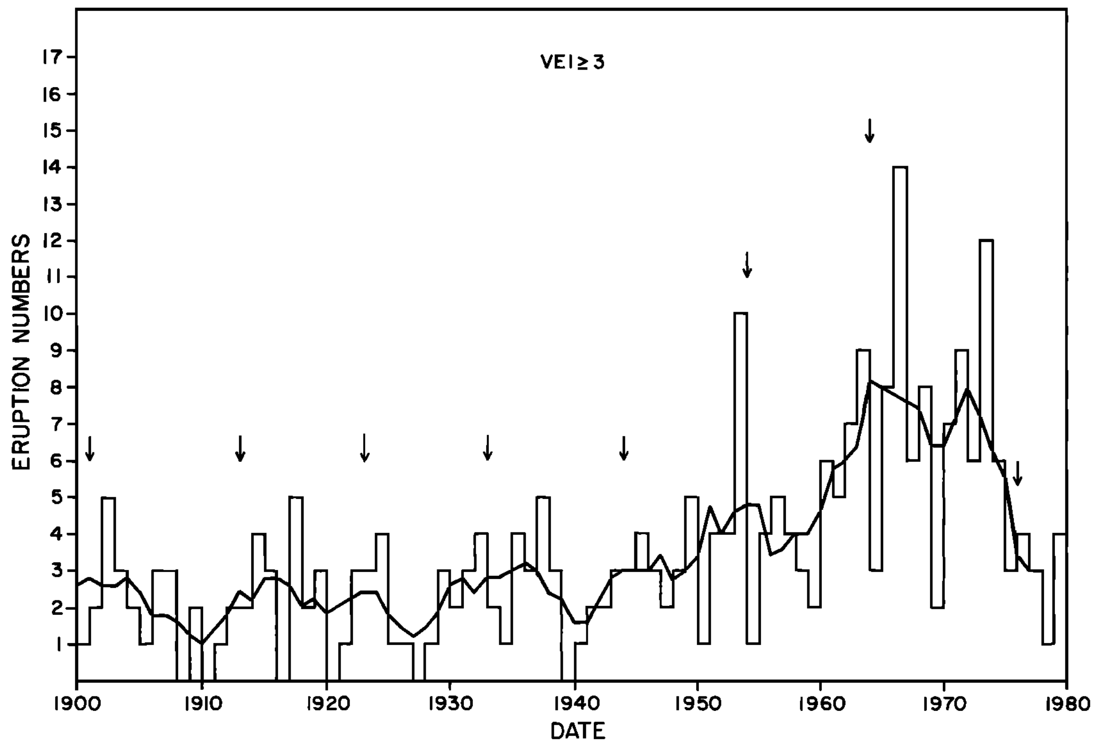

Fig. 5. Annual totals and 5-year running means of the numbers of VEI ≥ 3 eruptions between the years 1900 and 1979. The century-scale variation is essentially an artifact of eruption reporting, but the decadal variation is probably real. Arrows point to the years of sunspot minimum.

mum is not known, although small number fluctuations among the eruption numbers could be responsible.

The 80-Year Cycle and Longer Cycles

A long cycle of ~80 years also appears in the binned eruption data of Figure 1, and is clearest in the case of the largest eruptions with VEI ≥ 5. Spectral analysis of the 18 VEI ≥ 5 eruption dates reveals a very high spectral peak centered around a period of 80 years. However, since just four eruption maxima are covered in the available time series, a statistical test of significance (using assumed a priori periods of 70–90 years) yields only 85% confidence that this long cycle is not accidental. The available records of smaller eruptions are undoubtedly less complete and more affected by nonstationarities; this fact may account for the relatively low heights of the corresponding spectral peaks that occur at periods around 78 years for VEI ≥ 4 and around 71 years for VEI ≥ 3 (Figure 2).

An independent record of historic volcanic activity exists in an indirect form as excess sulfate acidity in glacial ice. The connection is the following: many volcanic eruptions are known to discharge copious sulfur gases, which react photochemically with water vapor in both the troposphere and the stratosphere to form aerosols. These aerosols are carried by winds far from their source and, in usually less than a year, completely fall out of atmospheric circulation. In an area of permanent ice, they are incorporated as acids in the distinct layer of new ice that is laid down each year. (Note that large eruptions producing little sulfur will not be recorded in the ice layers.) A detailed ice core record of annual sulfate acidity has been secured at Crête, Greenland, by *Hammer et al.* [1980]. The well-dated section covering the years 1500–1972 is now subjected to a standard Fourier spectral analysis. Since high-frequency noise in this type of indirect record of volcanism is a severe problem because of many unpredictable factors like the magnitude and relative sulfur richness of the eruptions, the proximity of the eruptions to Greenland, the seasonal shifts in tropospheric and stratospheric winds, and the nonvolcanic sources of atmospheric sulfate, it is not surprising that the ~11-year cycle does not show up strongly (either with or without subtraction of an estimated nonvolcanic background). The ~80-year cycle, however, does appear with a very high spectral power.

Instead of displaying the periodogram, a more straightforward way of demonstrating the long cycle and assessing its statistical significance is to bin the annual acidities in 40-year intervals, after subtracting both an outsized 9 μeq contribution from the uniquely large, geographically nearby Laki, Iceland, eruption of 1783 and an assumed uniform nonvolcanic background of 36 μeq per 40 years (μeq = microequivalent of H^+ per kilogram of ice). This assumed background [*Stothers*, 1984] is preferred here to the value of 48 ± 4 μeq per 40 years estimated by *Hammer et al.* [1980], because the latter value would produce a negative volcanic contribution in the 1920–1959 bin. However, the results turn out to be not very sensitive to the choice of assumptions about background acidity, bin size, and start date for the bin series, as long as the bins are large enough to minimize the high-frequency noise. Eight successive bins for volcanogenic acidities between 1640 and 1959 are plotted in Figure 6*a*, with parallel bins displayed below (in inverted form) for annual sunspot frequencies.

The reason for showing the sunspot frequencies is that a

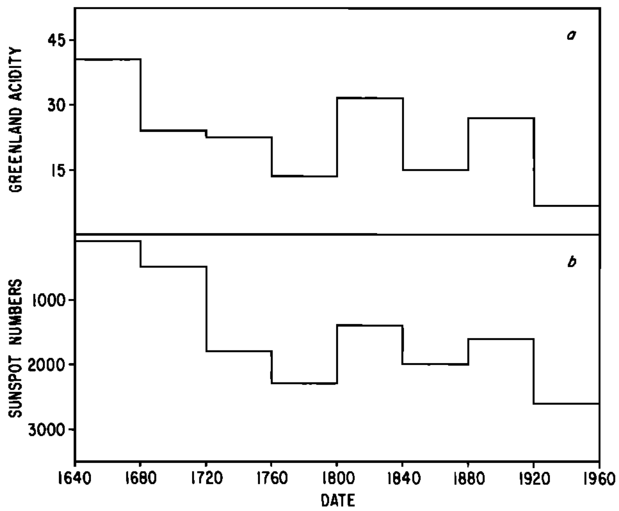

Fig. 6. Frequencies of volcanic and solar phenomena between the years 1640 and 1959 plotted in bins of width 40 years. (*a*) Volcanogenic acidity in the Crête, Greenland ice core, in units of μeq of H^+ per kilogram of ice. (*b*) Sunspot numbers on the Zurich system. Note that the scale of sunspot numbers is inverted.

solar quasi-period of 90 ± 10 years (called the Wolf-Gleissberg cycle) has long been recognized from the cyclical fluctuations of sunspot numbers at solar maxima and from the cyclical variability of the Schwabe-Wolf cycle lengths. The Wolf-Gleissberg cycle is the most prominent of the longer solar cycles. Its best-known manifestation is the protracted solar minimum (the so-called Maunder minimum) that occurred between the years 1645 and 1715 [*Eddy*, 1976, 1983].

The volcanogenic acidity record in Figure 6*a* is very clearly correlated with the sunspot frequency record in Figure 6*b*. The coefficient of linear cross-correlation is $r = -0.857$, which, with a crude allowance for serial autocorrelations in both time series [*Quenouille*, 1952], is significant at the 1% level. But volcanism and sunspots cannot, for obvious physical reasons, be linearly related, and therefore this application of the cross-correlation technique is not strictly valid. Adoption of rank orders of the frequencies in each time series obviates the problems of nonlinearities and serial correlations. The rank-order coefficient of linear cross correlation is $r = -0.929$, which is again highly significant at the 1% level. The ~80-year cycles of volcanism and solar activity, therefore, appear to run in parallel, though with a phase difference of about 180°, as is the case for the ~11-year cycles.

The whole record of volcanogenic acidity in the Crête ice core actually runs from 553 to 1972. Fourier analysis of this longer record shows that the ~80-year period is split into two components, 81 and 88 years, and that four additional slow periods exist, ~120, ~160, ~200, and ~350 years. No support is found for *Schofield*'s [1970] ~550-year volcanic cycle, but that cycle was based on *Lamb*'s [1970] very incomplete eruption catalog which covers too short a time span (469 years) to detect such a long period and displays a spurious large frequency maximum in the nineteenth century that produces the apparent periodicity. Even longer volcanic periods have been claimed by *Bryson and LaFontaine* [1988] using a 40,000-year record of radiocarbon-dated eruptions, but these periods are too long to check with the present ice core data.

Since auroral displays in the Earth's atmosphere represent proxy indicators of solar activity, time series analyses of aurorae can be used to study long-term solar behavior back to 500 B.C. Such analyses have yielded auroral periods of ~88, ~140, ~200, and ~350 years [*Schove*, 1955; *Link*, 1968; *Zhukov and Muzalevskii*, 1969; *Cole*, 1973; *Siscoe*, 1980; *Feynman and Fougere*, 1984]. Another proxy indicator of solar activity is the past production rate of carbon 14 in the Earth's atmosphere. This indicator also displays periods of ~85, ~140, ~220, and ~420 years [e.g., *Link*, 1966; *Sonett*, 1984; *Stuiver and Braziunas*, 1989]. Volcanic eruptions, therefore, tend to recur in patterns that are like those of the longer solar cycles.

QUASI-BIENNIAL CYCLE

At much shorter periods, power spectral analysis and autocorrelation analysis of monthly mean relative sunspot numbers have revealed a very weak [*Shapiro and Ward*, 1962; *Apostolov*, 1985], and possibly insignificant [*Rao*, 1973], quasi-biennial oscillation of solar activity with a mean period of 25 or 26 months. This oscillation has also been detected in other solar activity phenomena [*Kulčár and Letfus*, 1988] and may or may not be responsible for the quasi-biennial oscillation of the Earth's stratospheric winds. To look for a possible corresponding volcanic period, linear spectral analysis is applied to various short segments of the more densely populated part of the VEI ≥ 3 eruption time series between 1900 and 1980, by using only eruptions with unambiguously known months [*Simkin et al.*, 1981]. Although a high spectral peak is found at a period of 2.1 years, so are high peaks at 1.3, 1.7, 2.4, 3.3, and 4.8 years. Since these six periods approximately equal the periods of the six lowest harmonics (1.4, 1.7, 2.0, 2.5, 3.3, and 5.0 years) of a basic ~10-year period, they cannot be used, without supplementary information, to infer the existence of an independent 2.1-year period. In any case, a histogram of annual eruption numbers (Figure 5) shows no obvious evidence for such a quasi-biennial oscillation.

LONG-TERM LUNAR TIDAL CYCLES

None of the volcanic periods that appear in Figures 2 and 3 happen to be equal to the two long-term lunar tidal periods of 8.85 and 18.6 years. It might, nevertheless, be thought that the minor spectral peaks in the volcanic spectra around 9.1 and 19.1 years are close enough in period to be relevant. However, the lunar tidal cycles (unlike the solar activity cycles) are strictly periodic in nature, so that any small mismatch with a tentatively associated volcanic period would lead to a phase discrepancy that accumulates over time. For both spectral identifications suggested above, the tidal cycles would be completely out of phase with the volcanic cycles in only two centuries (half the available record length).

Kluge [1863*a*], using his unpublished volcanic eruption catalog, and *Hamilton* [1973], employing *Lamb*'s [1970] catalog, found an exceptionally large eruption frequency maximum centered around the year 1822, which *Hamilton* [1973] related to the occurrence of a unique lunar tidal maximum in 1821. However, the much more substantial catalog of *Simkin et al.* [1981] shows no evidence for such a volcanic maximum, since successive annual numbers of VEI $\geq$ 0 eruptions for the 9 years centered on 1822 deviate by at most 1σ from the mean number over this period. Long-term lunar tidal effects, if they exist at all in the volcanic record, must be well submerged in the noise. Although *Alexeev* [1989] has recently claimed a period of $\sim$17 or $\sim$22 years for essentially the smallest eruptions during the period 1760–1980, the discrepancy between these values and 18.6 years is very large.

Possible Mechanisms

The physical link between volcanic eruptions and solar activity can only be conjectured at present. Because of the large amount of randomness in the volcanic record, the link is probably not very direct, and solar activity probably acts only as a minor forcing agent that reduces slightly the probability of an eruption by a particular volcano, independently of its geographical latitude.

What astronomical factors might be involved in this link? It is known that the surface activity of the Sun produces variations in its electromagnetic and corpuscular emissions, which consist of both continuous (photospheric) and sporadic (flare) components. The variable part of this solar radiation must produce a small incremental heating or cooling of the Earth's atmosphere on which it impinges. It is now fairly certain that the $\sim$11-year solar cycle is manifested in weak regional (and probably global) changes of the Earth's weather, as indicated by measurements of surface pressure, temperature, precipitation, and zonal wind patterns [*Kelly*, 1977*b*; *Currie*, 1987; *Labitzke*, 1987; *Labitzke and van Loon*, 1989]. Surface temperatures and precipitation probably also follow the $\sim$80-year solar cycle [*Willett*, 1974; *Hameed et al.*, 1983; *Hameed*, 1984; *Reid*, 1987]. For both cycles, cooler and wetter years tend to occur around the times of solar minimum.

A more direct consequence of the disturbed circulation patterns of the Earth's air masses is a slight alteration of the Earth's total moment of inertia and of its atmospheric angular momentum. To conserve the Earth's total angular momentum, its interior rate of rotation adjusts, as reflected in the measured length of the day. These changes in the length of the day must be relatively prompt as they are known to track the seasonal changes of insolation [*Lambeck and Cazenave*, 1973]. They have also been detected with the same periods as the $\sim$11-year solar cycle [*Challinor*, 1971; *Currie*, 1981] and some of the slower solar cycles as well [*Link*, 1961; *Kiselev*, 1981], and they have probably also occurred right after very large individual solar flares [*Danjon*, 1962*a*, *b*; *Gribbin and Plagemann*, 1973].

There seem to be two plausible ways, therefore, by which atmospheric disturbances may affect volcanic eruptions. One way involves the small abrupt changes in the Earth's rate of rotation. Associated torques in the solid Earth might then trigger a host of minor earthquakes [*Anderson*, 1974] and thus create (or widen) numerous small fissures in already stressed rock like that surrounding volcanic magma chambers. Magma intruding into these openings would temporarily relieve some of the pressure in the chambers themselves. This could appear as a small, premature eruption. In a threshold situation, an imminent large eruption could thereby be lessened in intensity or else delayed, or possibly even aborted. As a result, slightly fewer large eruptions would be expected to occur close to the years of solar maximum compared with other phases; a correspondingly greater number of large eruptions should occur loosely distributed around the years of solar minimum.

A specific prediction of this particular model is that small earthquakes should occur somewhat more frequently near the times of solar maximum. In fact, many studies have already shown that this is the case [e.g., *Davison*, 1938; *Machado*, 1960; *de Mendoça Dias*, 1962; *Afanas'yeva*, 1963; *Simpson*, 1967; *Tamrazyan*, 1968]. Furthermore, *Singh* [1978] has determined that swarms of very small earthquakes (microearthquakes) follow immediately after important individual solar flares. Also consistent with the proposed model is the fact that *Gutenberg and Richter* [1965] and *Meeus* [1976], using more data than *Sytinskiy* [1963], were unable to find a significant correlation with solar activity for the very largest earthquakes, which appear to be randomly distributed in time.

The proposed earthquake pressure release mechanism, which temporarily reduces the rate of occurrence of large volcanic eruptions, may concomitantly work to increase the frequency of smaller eruptions, although the present VEI $\leq$ 2 data seem to be inadequate to look for such long periods. If this idea is correct, another mechanical forcing mechanism, the fortnightly lunar-solar tides, may likewise tend to trigger small eruptions. Many studies have in fact already demonstrated that small volcanic eruptions [*Jensen*, 1904; *Perret*, 1908; *Wood*, 1917; *Jaggar*, 1920; *de Mendoça Dias*, 1962; *Johnston and Mauk*, 1972; *Mauk and Johnston*, 1973; *Hamilton*, 1973; *Bullard*, 1976; *Mauk*, 1979; *Dzurisin*, 1980] as well as swarms of volcanic earthquakes [*de Mendoça Dias*, 1962; *Filson et al.*, 1973; *Mauk and Kienle*, 1973; *Golombek and Carr*, 1978; *McNutt and Beavan*, 1981, 1984; *Dzurisin et al.*, 1984; *Mori et al.*, 1989] and closely related minor volcanic phenomena like sulfur dioxide emissions [*Stoiber et al.*, 1986; *Connor et al.*, 1988] and geyser activity [*Rinehart*, 1972*b*] follow to some extent a fortnightly cycle.

A second way by which global atmospheric perturbations might influence volcanic eruptions is through changes in annual precipitation. Observed increases in rainfall and snowfall around the years of solar minimum must lead to temporarily larger reservoirs of ground water in and near volcanic vents. Seepage of this water into volcanic magma chambers might then be able to trigger eruptions in certain cases that are close to threshold. Since the average diffusion time for the stored water probably exceeds 1 year [*Casetti et al.*, 1981], an accompanying annual volcanic cycle due to the large seasonal changes in precipitation might not occur at a detectable level; indeed, such a cycle seems not to exist on either a global or a zonal scale [*Stothers*, 1989]. Although the small increases in annual mean precipitation during the courses of the $\sim$11- and $\sim$80-year cycles are unlikely to have a marked impact on the aqueous content of volcanic country rocks that are mostly already saturated, the apparent excess of volcanic eruptions around solar minimum is likewise very small. Therefore the required triggering mechanism need not be (and, in fact, really cannot be) very strong.

Summary and Predictions

The historical record of large volcanic eruptions from 1500 to 1980, as contained in the *Simkin et al.* [1981] and *Newhall* *and Self* [1982] catalogs, reveals two weak, but probably statistically significant, periodicities of ~11 and ~80 years. The ~80-year cycle is also seen in the record (from 553 to 1972) of volcanogenic acidities in the Crête, Greenland, ice core that *Hammer et al.* [1980] analyzed. Both cycles appear to correlate with solar activity, and in both cases the incidence of volcanic eruptions is slightly greater around the times of solar minimum than at other phases. A striking example, noted also by *Fairbridge* [1980], occurred during the long Maunder minimum (1645–1715) in solar activity, which was apparently reflected in abnormally high volcanic eruption numbers (partly artificial for VEI = 3) as well as in elevated Greenland ice acidities. Even slower solar cycles of ~120 to ~350 years appear in the acidity record. The quasi-biennial solar cycle has not been detected in the volcanic eruption data. Nor does the eruption record show any reliable evidence of the slow lunar tidal cycles of 8.85 and 18.6 years. No dependence of the results on geographical latitude zones of the volcanoes appears to be present.

Mechanisms that might link the increase in frequency of large volcanic eruptions to quiet periods in solar activity probably involve changes in the basic state of the atmosphere. Such changes must surely include, first of all, the known alterations in circulation patterns of the principal air masses during a solar cycle. If these changes are abrupt, such as after large solar flares, they can alter the Earth's axial spin and thereby trigger small earthquakes which may temporarily relieve some of the stress in volcanic magma chambers. This "safety valve" mechanism would then immediately reduce the short-term probability of having a large volcanic eruption. A second effect of solar-induced atmospheric changes is the tropospheric warming and reduced precipitation around the years of solar maximum. The balance of the precipitation is made up around solar minimum, at which time the possibility of phreatomagmatic eruptions becomes momentarily more favored. Although both atmospheric effects are clearly very small, so are the minor excesses and deficits of eruption numbers that define the two volcanic cycles.

Feedback on the atmosphere from the two cycles is expected to come from enhanced sulfur loading of the stratosphere around the years of solar minimum. When the Sun is least active, volcanogenic aerosols should be present in the stratosphere in greater numbers, temporarily overwhelming the tiny aerosol background (which itself has been observed to decrease around the time of solar minimum) [*Hofmann and Rosen*, 1982]. At the same time, the Sun's intrinsic luminosity is slightly reduced below its mean value [*Willson and Hudson*, 1988; *Lean and Foukal*, 1988]. Both of these external factors lower the amount of solar radiation absorbed by the troposphere, and thereby induce cooler worldwide average surface temperatures [*Hansen et al.*, 1981] as well as various other atmospheric anomalies [*Lamb*, 1970].

Anderson [1974] has suggested a rather different model, in which the presence of a volcanic aerosol veil alters the atmospheric circulation enough to change the Earth's rate of rotation, triggering an excess of earthquakes. Both models may be correct, and if so, *Anderson*'s [1974] mechanism provides a degree of negative feedback and therefore may account in part for the weakness of the solar signal in the volcanic record.

From a global perspective, volcanic eruptions are relatively random events, and the two small quasi-periodic components are difficult to quantify, especially in terms of aerosol production. In addition, an isolated volcanic eruption of large magnitude can have a temporary climatic impact much greater than that due to the mean volcanic background [*Rampino et al.*, 1988]. In spite of these problems and of the remaining possibility that the derived quasi-periodicities are just statistical artifacts, appropriate volcanic forcing terms will have to be included in future global climate modeling. The present results provide a first reconnaissance of the statistical problems involved.

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